Dwarf galaxies in a Self-Interacting Dark Matter Universe

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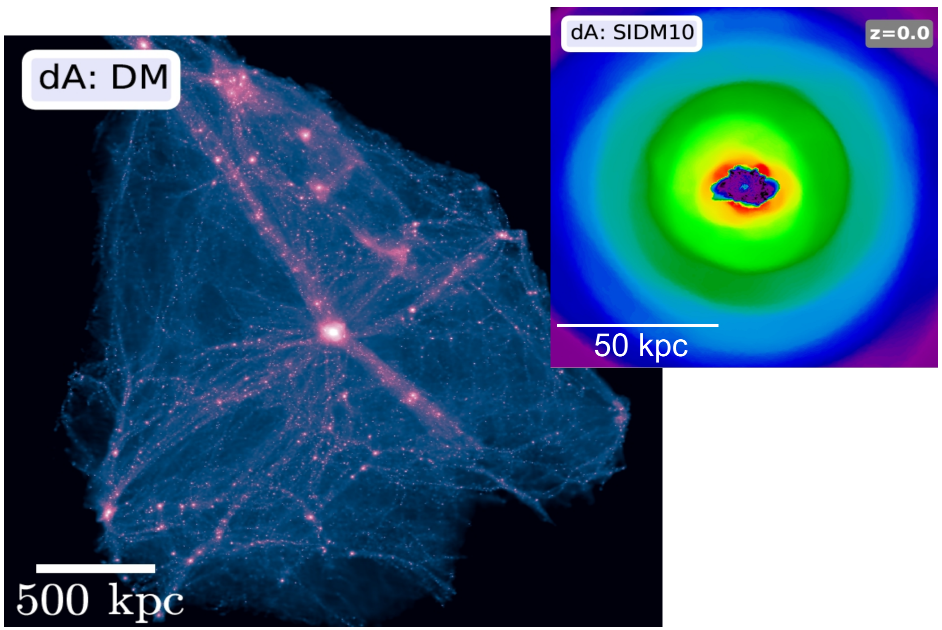
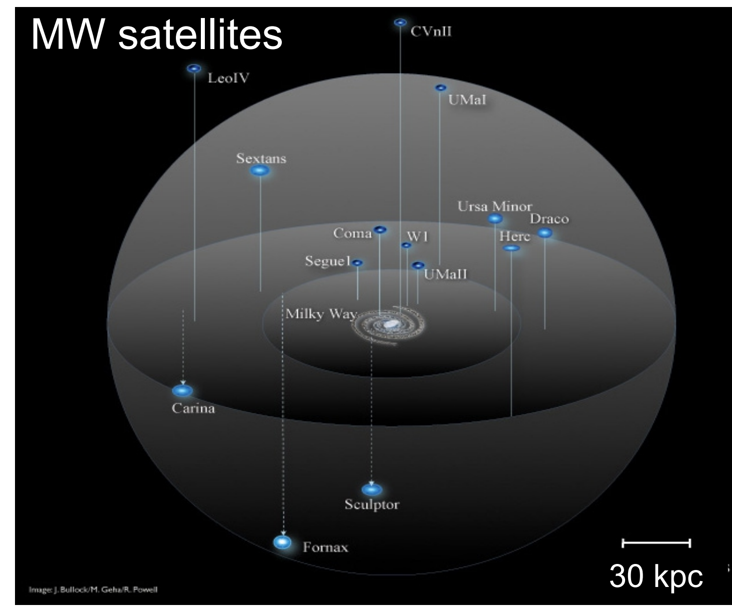
Dark Cosmology Centre





Collaborators: Mark Vogelsberger (MIT, US), Avi Loeb (ITC, US),
Matt Walker (CMU, US), Matt Buckley (Rutgers, US),
Kris Sigurdson (UBC, Canada), Francis-Yan Cyr-Racine (NASA, JPL)

11th Potsdam Thinkshop: Satellite galaxies and dwarfs in the local group, August 2014

Opening remarks

CDM/WDM/SIDM are by themselves incomplete DM theories

They are effective structure formation theories that need completion from a particle physics model (all beyond SM: "exotic")

Opening remarks

In the standard CDM paradigm galaxies
form in a purely gravitational DM background

The nature of DM as a particle is therefore
irrelevant for galaxy formation and evolution

There is however, **no strong evidence**
to support this **strong** hypothesis

Although there is no indisputable evidence
that the CDM paradigm is wrong, there are reasonable
physical motivations to consider alternatives

DM nature and structure formation

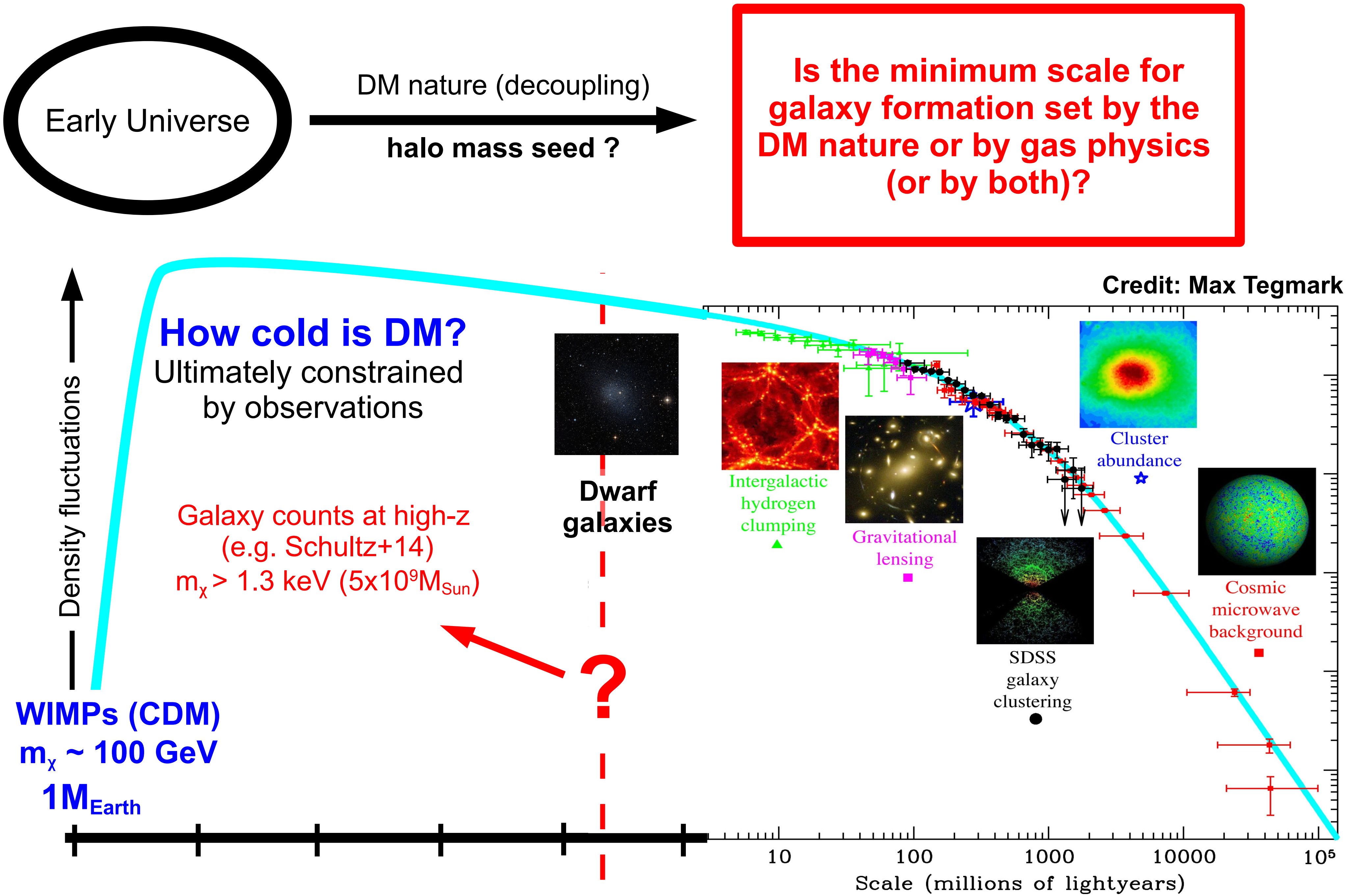
Early Universe

DM nature (decoupling)

halo mass seed ?

Is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?

DM nature and structure formation



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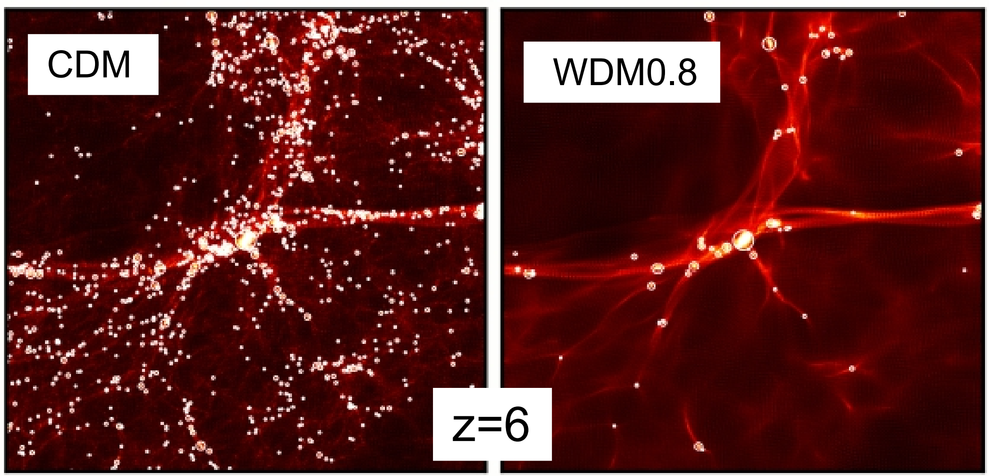
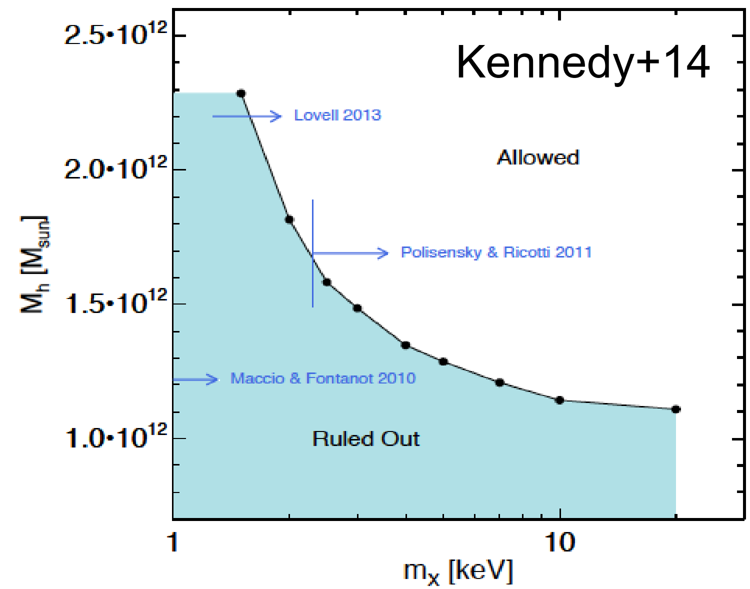
Galaxy counts at high redshift ($m_\chi >$ 1.3 keV, Schultz+14)



MW-satellite counts



Ly-α forest constraints ($m_\chi >$ 3.3 keV, Viel+13)

Also, subhalo-satellite counts on M31 ($m_\chi >$ 1.8 keV, Horiuchi+13)

DM nature and structure formation

Early Universe

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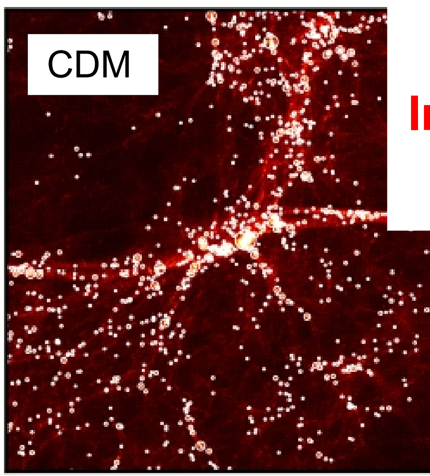
halo mass seed ?

Is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?

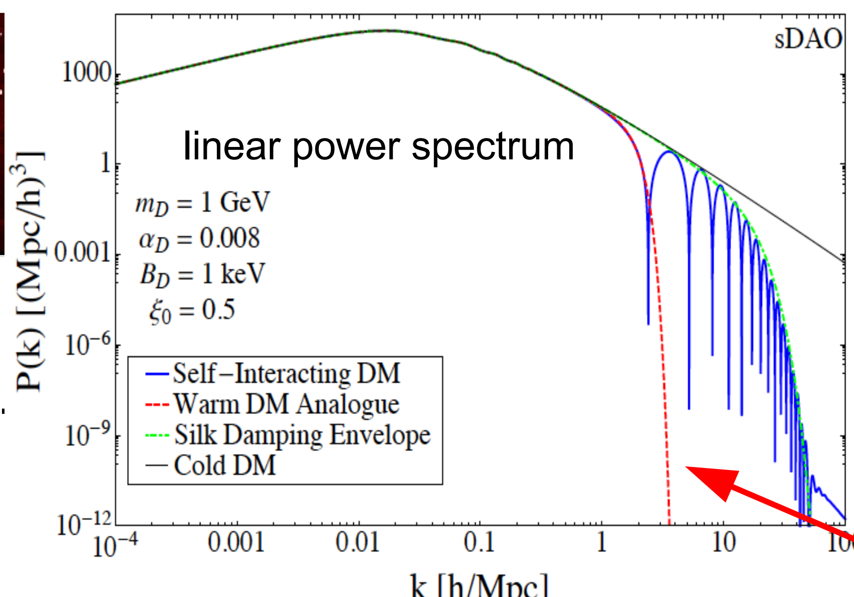
Most constraints based on thermal-like power spectrum cut-off!!

Important to consider before answering this question generically

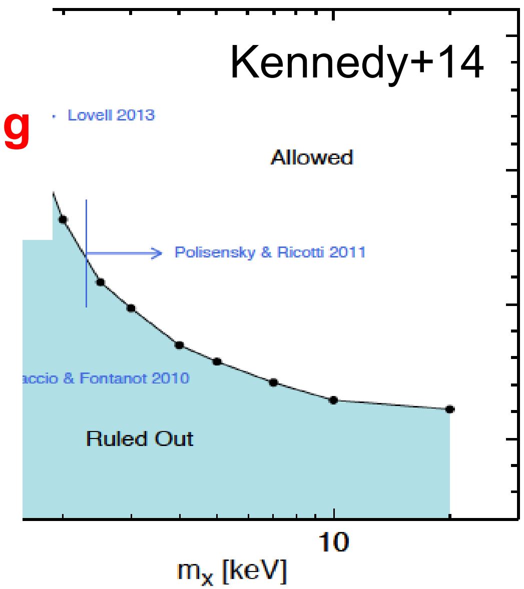
Galaxy counts at high re



Ly-α forest constrain



MW-satellite counts



halo-satellite counts on M31

> 1.8 keV, Horiuchi+13)

thermal (free-streaming) cut-off

Structure formation and DM interactions

Onset of structure formation

halo mass seed $\xrightarrow[\textbf{DM interactions ?}]{\text{DM nature}}$ **Are non-gravitational DM interactions irrelevant for galaxy formation?**

Structure formation and DM interactions

Onset of structure formation

halo mass seed $\xrightarrow[\textbf{DM interactions ?}]{\text{DM nature}}$ **Are non-gravitational DM interactions irrelevant for galaxy formation?**

DM particle interactions (weak scale) **hoped** by most detection efforts!!

Cross section σ/m_χ [cm^2/gr]	Characteristic velocity $\tilde{v}$ [km/s]
SI $\chi-$nucleon $\lesssim \underline{10^{-23}}$	~ 200
$m_\chi \in (0.1-5)$ TeV	(local halo)
LUX	
$\chi\chi \to b\bar{b}$ $\lesssim \underline{10^{-10}}$	~ 10
$m_\chi \in (0.1-1)$ TeV	(dSphs)
Fermi-LAT	

1 cm^2/g ~ 2 barns/GeV

Does it interact with ordinary matter?

χ-nucleus interactions extremely low to impact structure information

Does it interact with itself (annihilation)?

χ−χ self-annihilation extremely low to impact structure information

Structure formation and DM interactions

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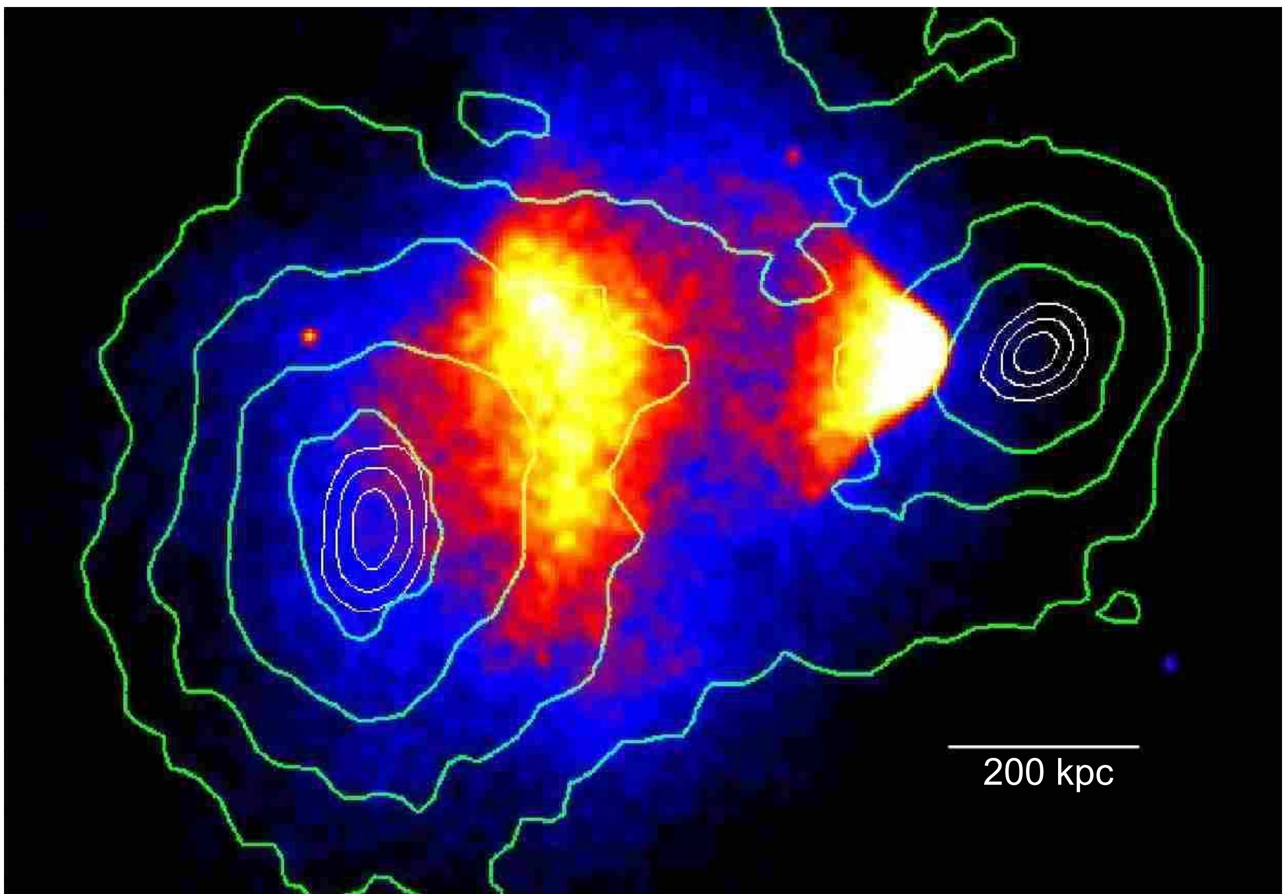
Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?

Bullet Cluster (Clowe +06)



(Randall+08)

$\sigma/m < 1.25\ cm^2/gr$

Improvements to constraints from merging clusters hopefully coming soon!

MERGING CLUSTER COLLABORATION

Structure formation and DM interactions

Onset of structure formation

halo mass
seed

DM nature

DM interactions ?

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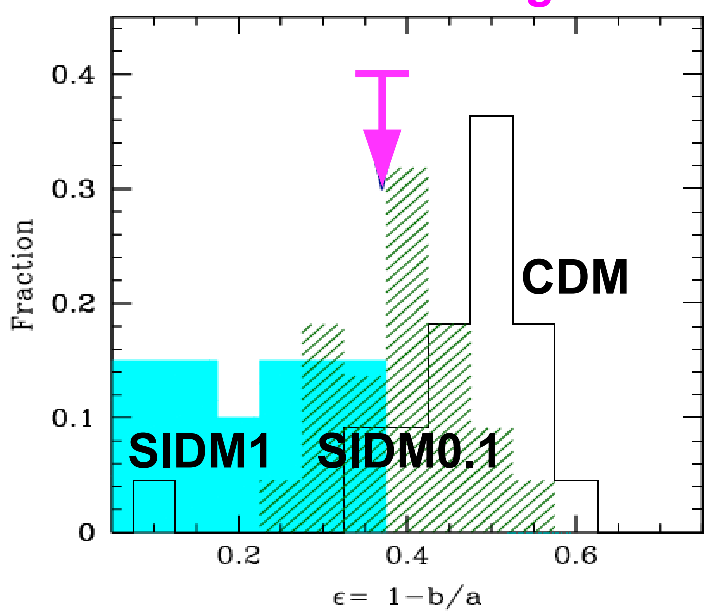
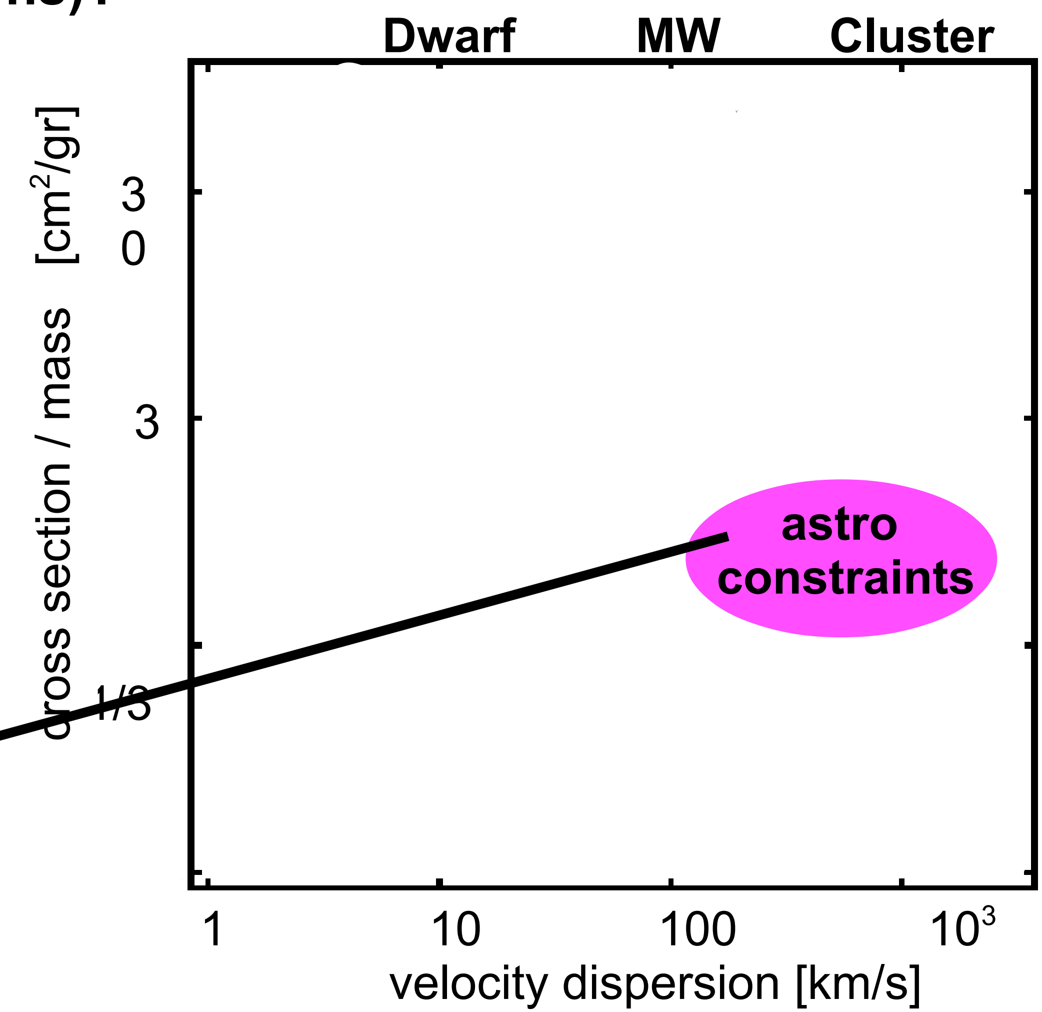
Does it interact with itself (collisions)?

Collisions make DM haloes more spherical

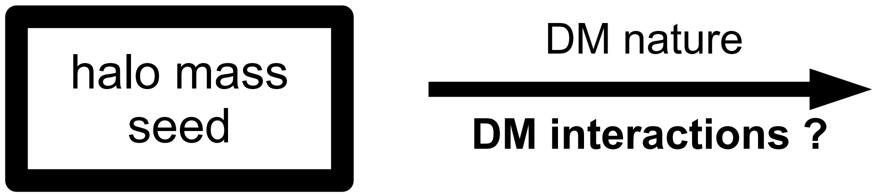
ellipticity constraint NGC 720 (Peter+2013) $\sigma/m < 1\ cm^2/gr$





Structure formation and DM interactions

Onset of structure formation



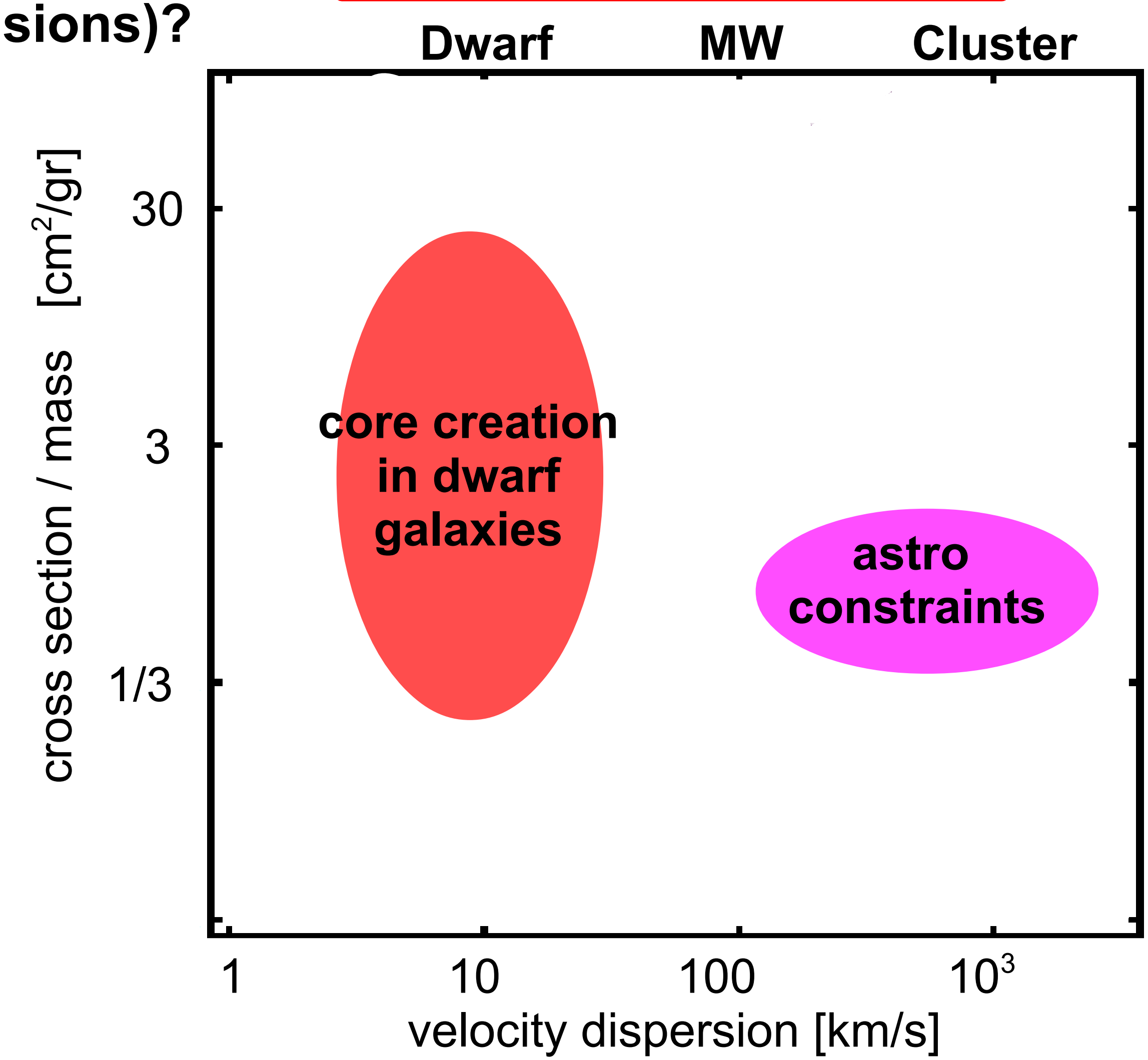
Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?

Constraints allow collisional DM that is astrophysically significant in the center of galaxies:

~ <1 scatter/particle/t_H>

DM phase-space distribution changes



Structure formation and DM interactions

Onset of structure formation

halo mass seed

DM nature → DM interactions ?

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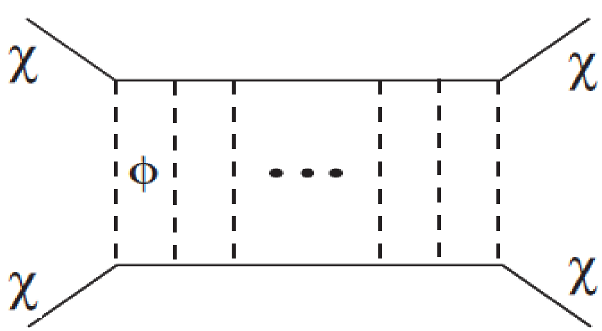
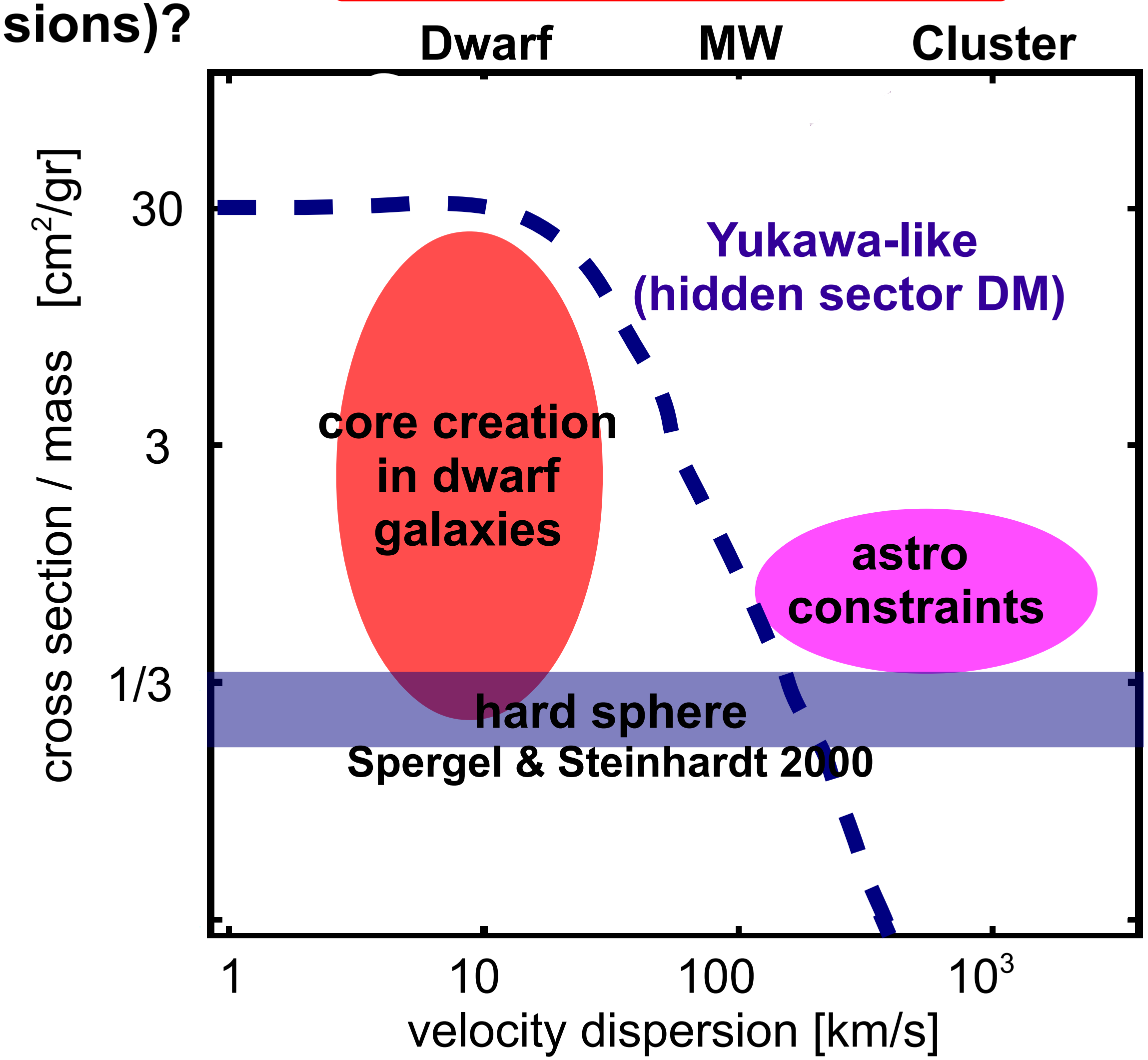
Does it interact with itself (collisions)?

vdSIDM models motivated by a new force in the "dark sector", e.g. Yukawa-like, Feng+09



nucleon-nucleon elastic scattering: ~10 cm^2/g !!



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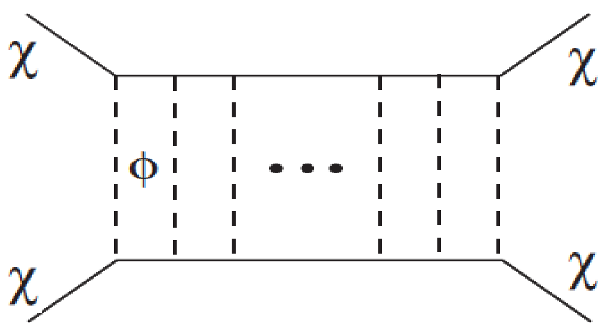
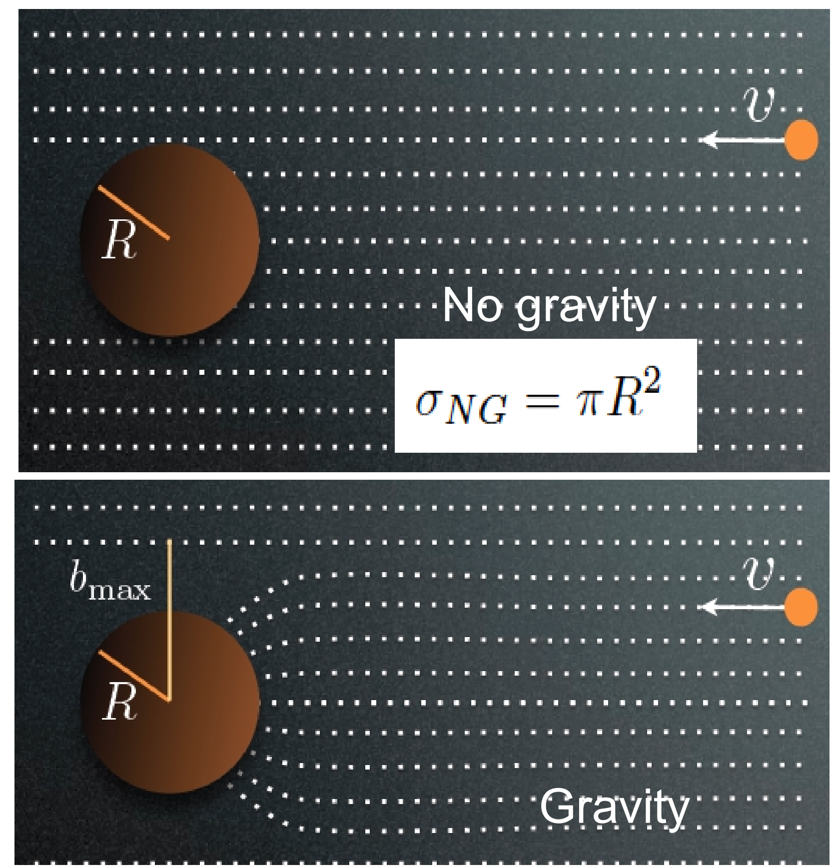


nucleon-nucleon elastic scattering: ~10 cm^2/g !!

Classical analogue



$$\sigma_N = \sigma_{NG}\left(1 + \frac{v_{esc}^2}{v^2}\right) = \pi b_{max}^2$$

Fig. from M. Cirelli, DMV, Cambridge 2011

Structure formation in a SIDM Universe

Early Universe

DM nature (decoupling)

Global abundance

halo mass seed

Onset of structure formation

DM nature (self-interactions)

SIDM

galaxy formation and evolution (gas and stellar physics)

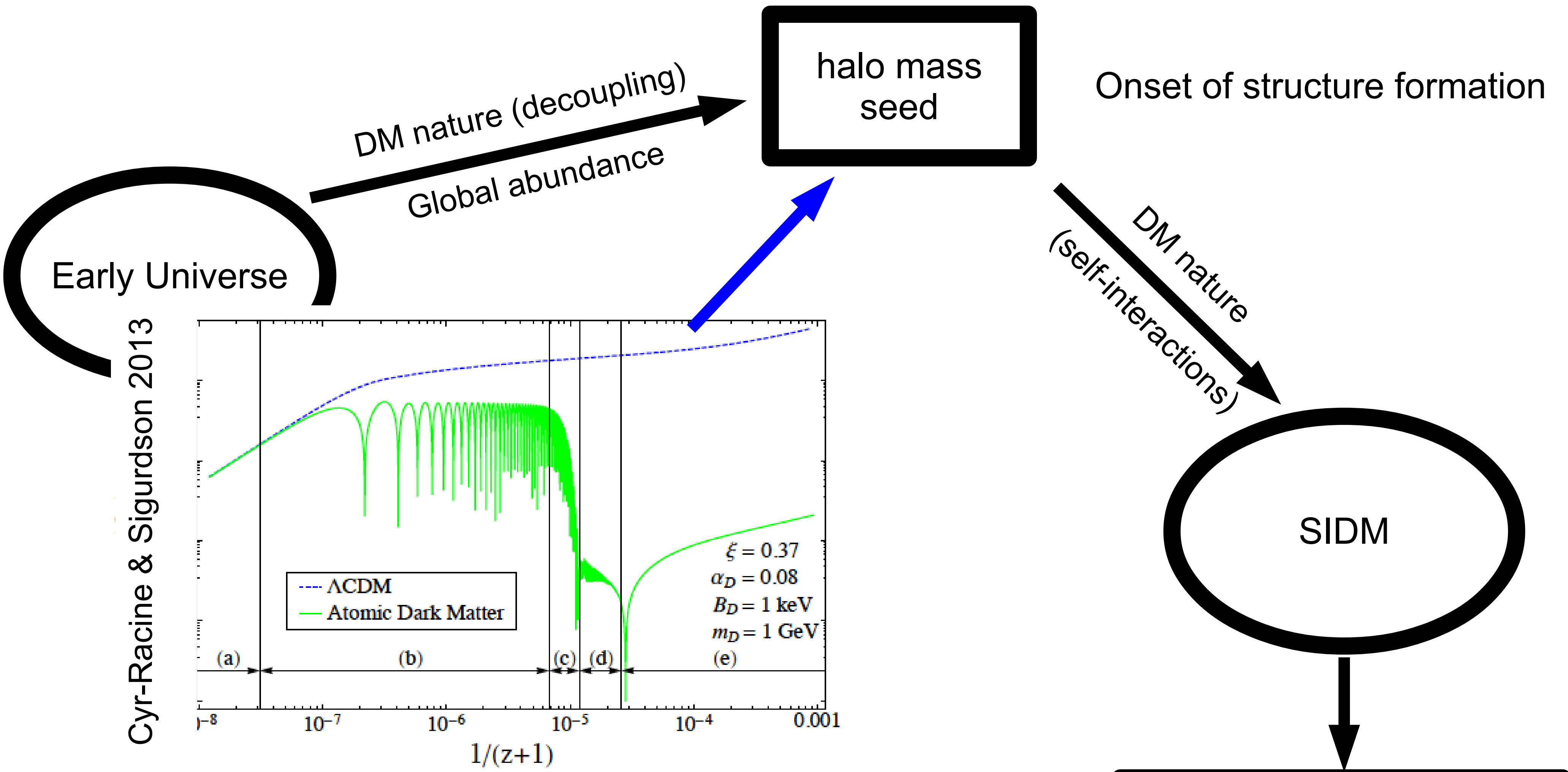
Pioneer N-body SIDM simulations (same P(k) as CDM):

Yoshida, Springel, White & Tormen 2000
(constant cross section)

Davé, Spergel, Steinhardt & Wandelt 2001
(constant cross section)

Colín, Avila-Reese, Valenzuela & Firmani 2002
(velocity-dependent: power-law)

Structure formation in a SIDM Universe



Interactions between DM and relativistic particles
(e.g. dark radiation) in the early Universe introduce collisional damping and "dark" acoustic oscillations into the linear power spectrum

Structure formation in a SIDM Universe

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DM nature (decoupling)

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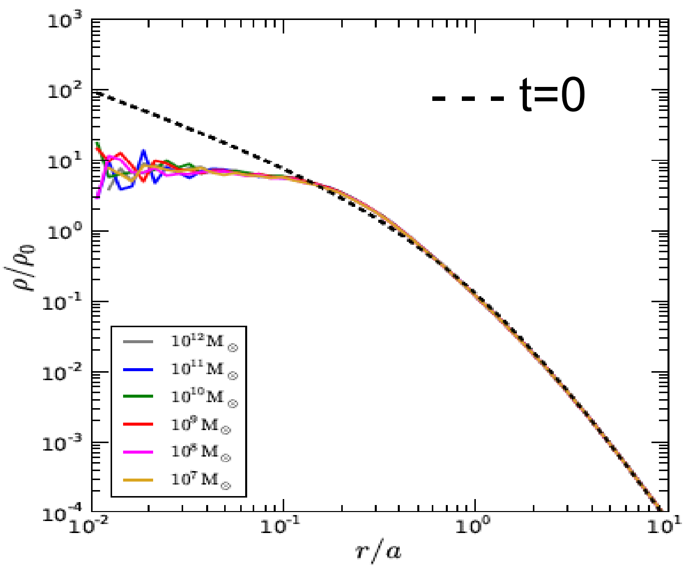
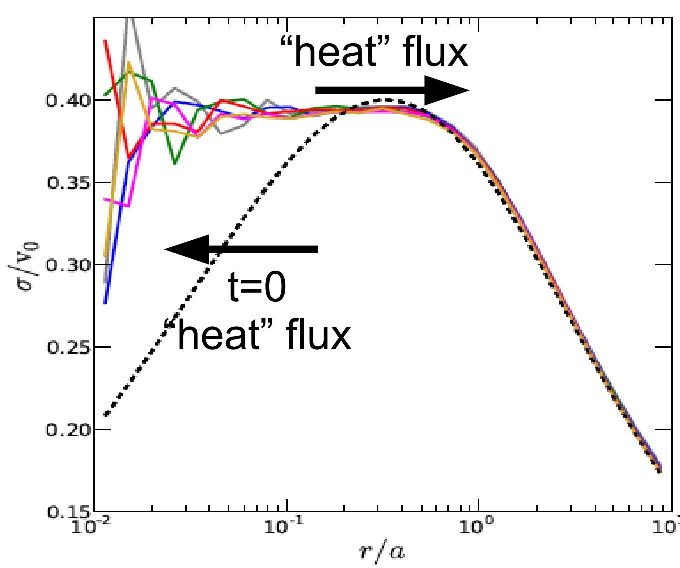
DM nature (self-interactions)

SIDM

DM self-collisions (elastic so far!)
probabilistic approach





Collisional Boltzmann equation

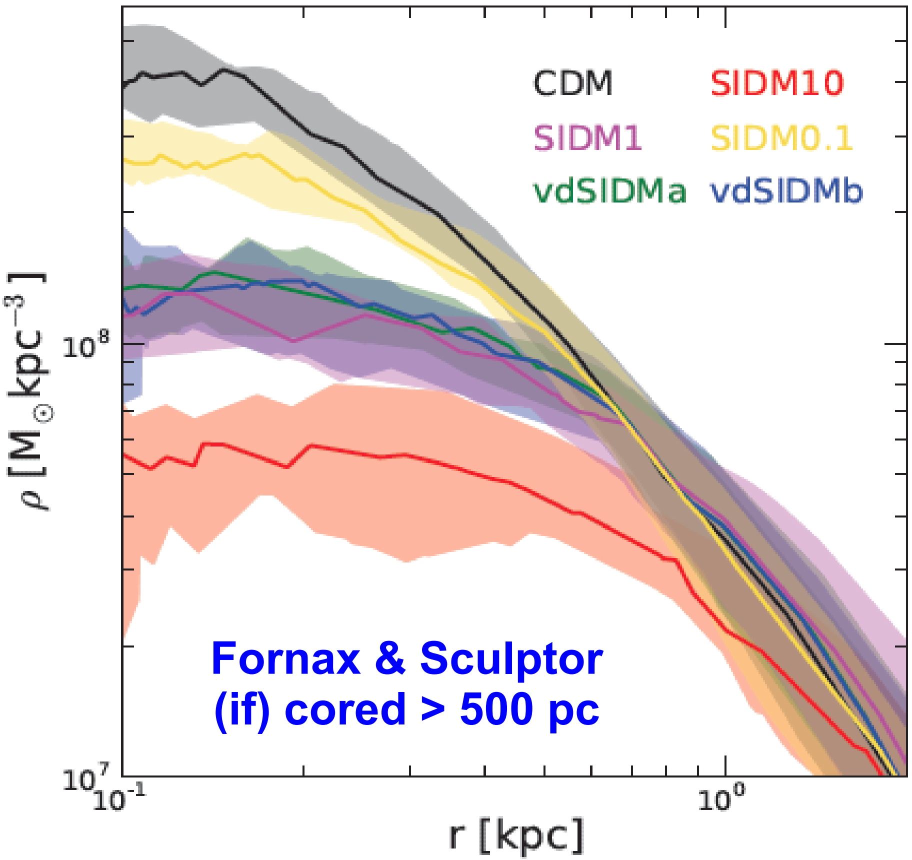
$$\frac{df}{dt} = C[f, \sigma_{\rm sc}] \quad \rightarrow \quad \frac{d\rho_\chi}{dt} \sim -\rho_\chi^2 \left(\frac{\sigma_{\rm sc}}{m_\chi}\right) \sigma_{\rm vel}$$

galaxy formation and evolution (gas and stellar physics)

DM collisions and substructure

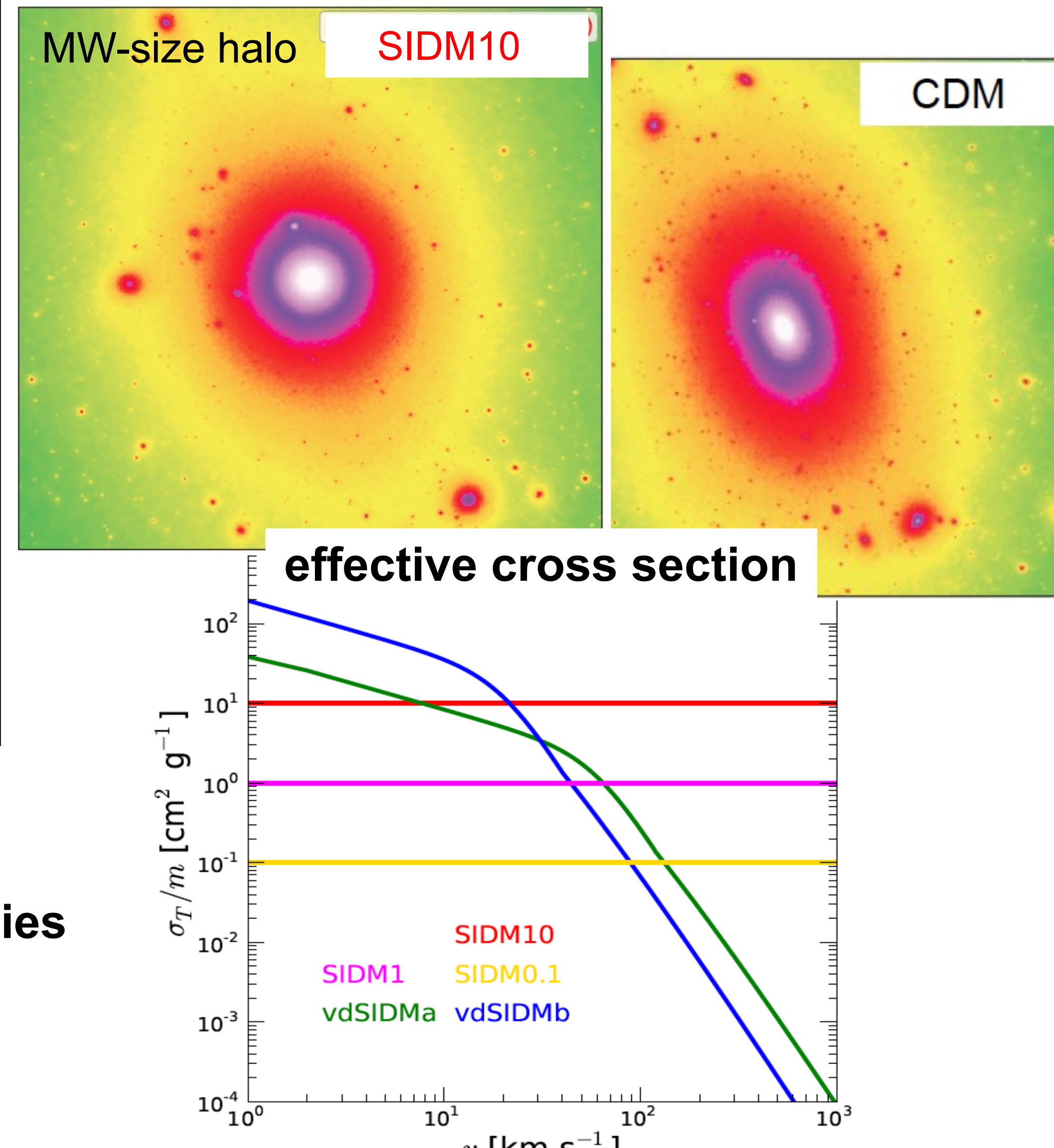
The dark satellites of a MW-size halo SIDM-only simulation

Zavala, Vogelsberger & Walker 13



collisions reduce central DM densities creating core-like profiles

Vogelsberger, Zavala & Loeb 12



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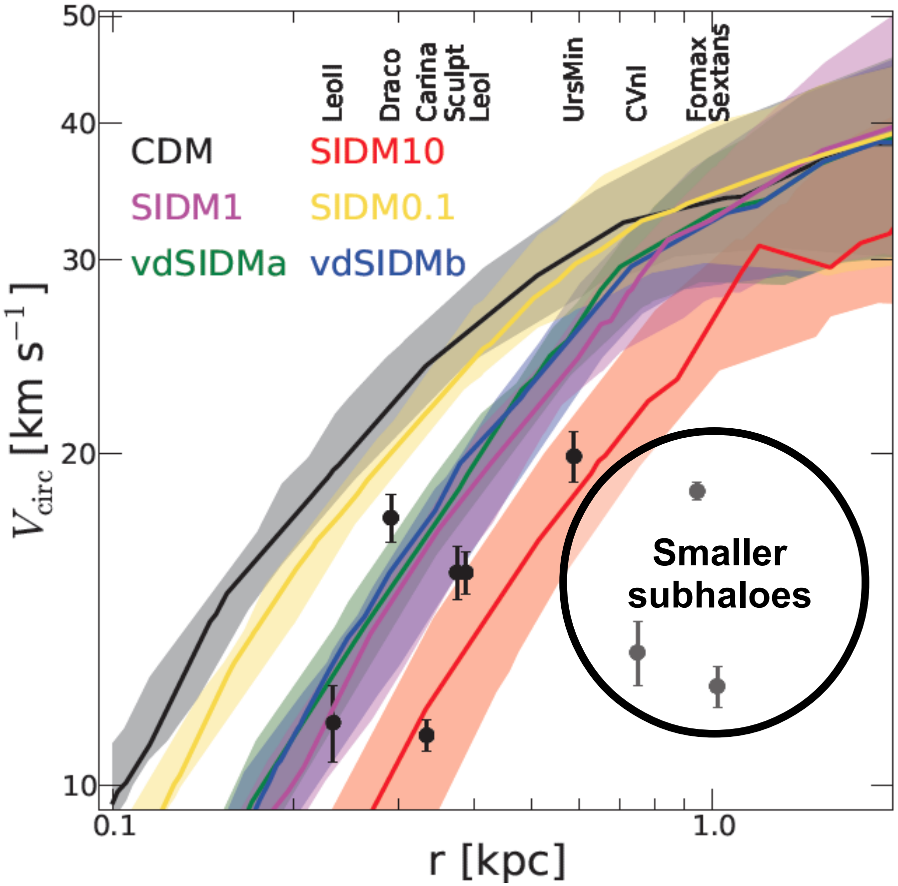
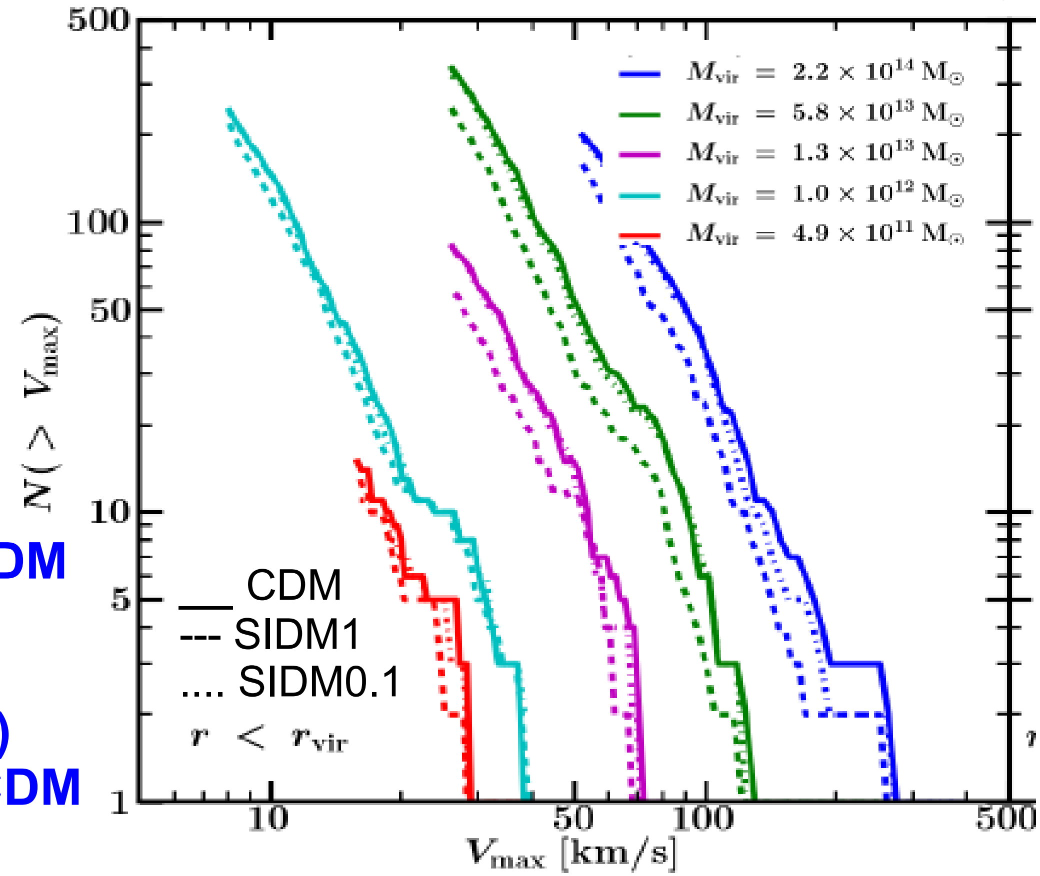


Elastic SIDM only works as a ***distinct DM-only*** alternative to CDM **if 0.6 cm^2/g < σ / m < 1 cm^2/g or velocity-dependent (MW-halo-mass-dependent)**

Subhalo mass function

Rocha+13

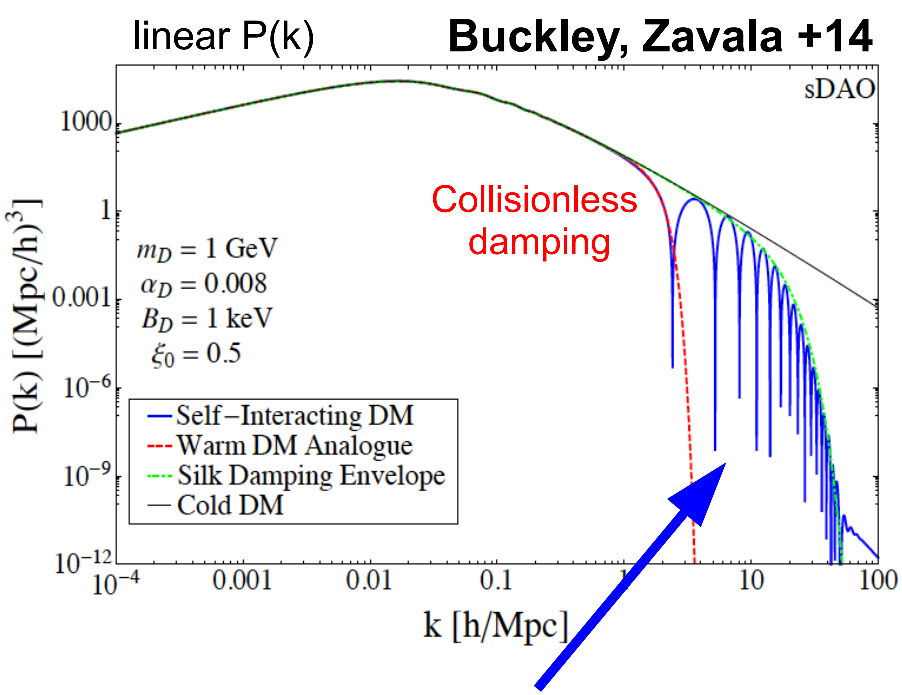


Allowed *elastic* SIDM significantly reduces the inner structure tension of CDM ("too big to fail" and "core-cusp")

Allowed *elastic* SIDM (with CDM P(k)!!) faces the same abundance challenge of CDM

A richer DM (initial) power spectrum

Reducing small-scale power suppresses the formation of low-mass haloes and delays that of massive ones: WDM (e.g. Bode+01) CDM+interactions (e.g. Boehm+02)



Collisional damping:
e.g. photons (γCDM, Boehm+14), dark radiation (ADM, Cyr-Racine+13)

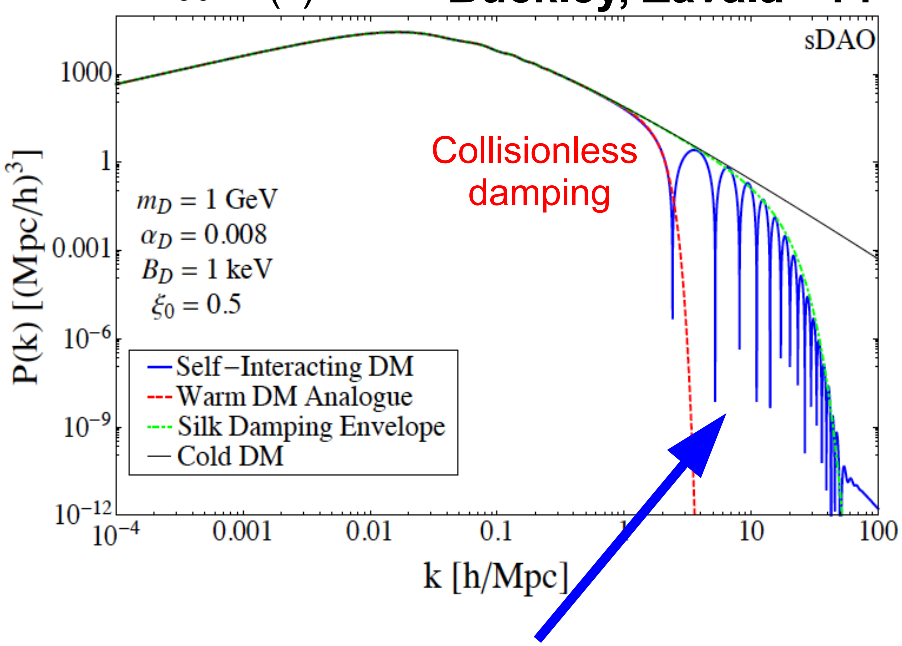
With an additional scale in P(k), these models are expected to avoid Ly-α forest constraints impacting halo abundance in a significant way

Models consistent with Planck CMB data

A richer DM (initial) power spectrum

Reducing small-scale power suppresses the formation of low-mass haloes and delays that of massive ones: WDM (e.g. Bode+01) CDM+interactions (e.g. Boehm+02)

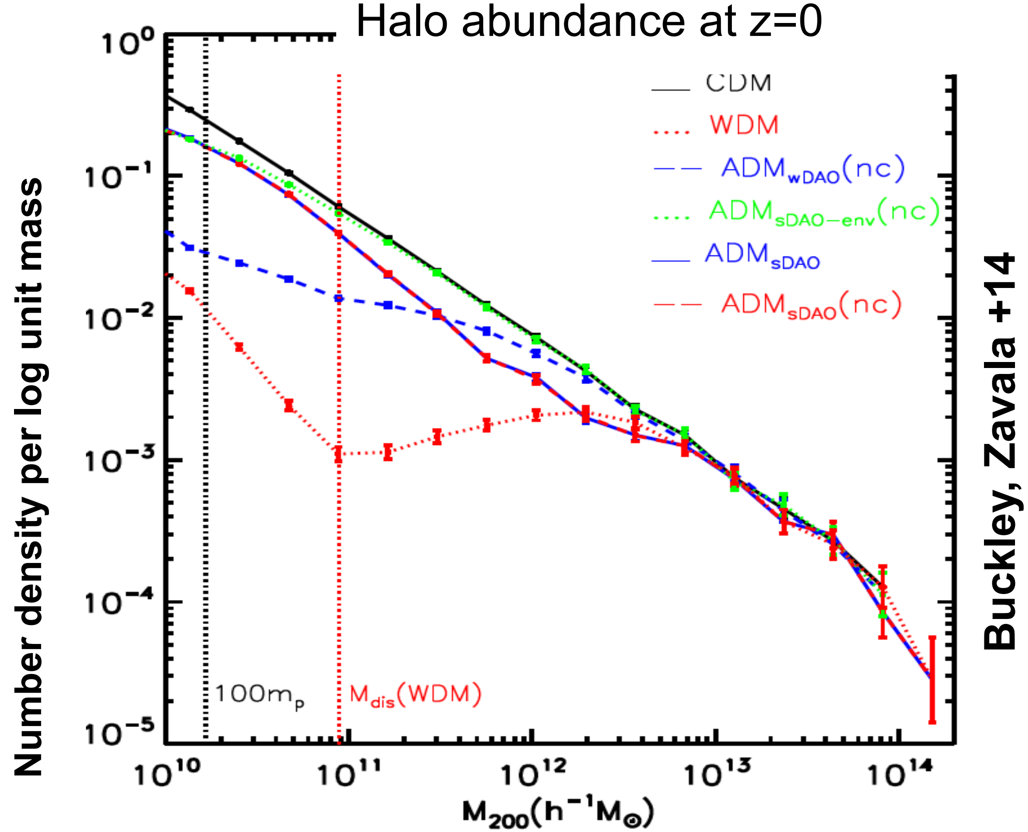
linear P(k) **Buckley, Zavala +14**



Collisional damping:
e.g. photons (γCDM, Boehm+14), dark radiation (ADM, Cyr-Racine+13)

NON-LINEAR EVOLUTION (N-body simulations)

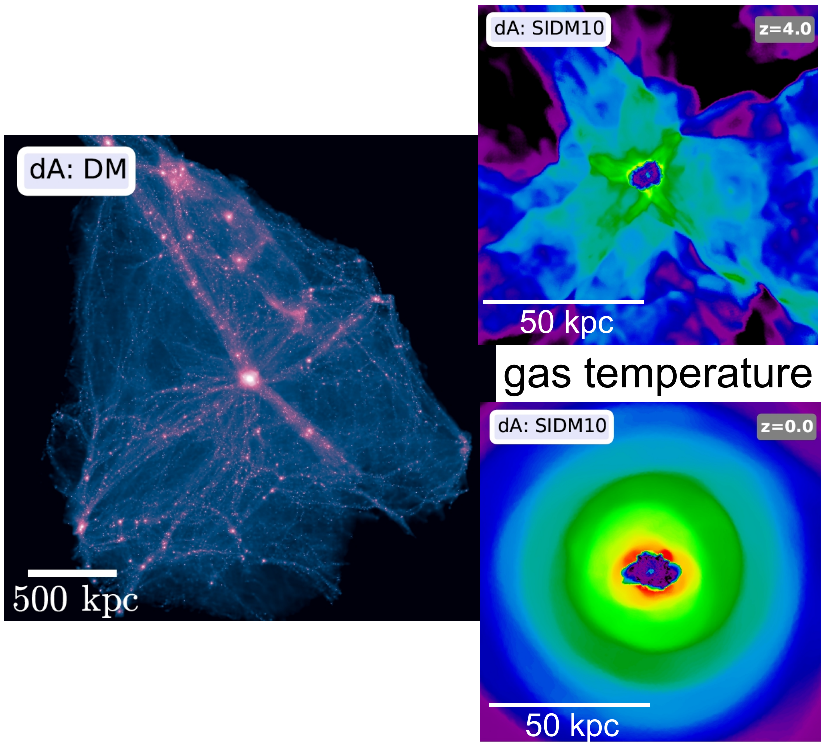
Halo abundance at z=0



Their effects of DAO's are still visible at z=0!! (potential to solve the CDM abundance problem: proof of concept only)

Galaxies in a SIDM Universe

How does galaxy formation occurs in SIDM? Will the coupling of baryonic physics and DM collisionality help (or hinder) constrain SIDM models?



- baryonic physics implementation (Illustris): hydro, star formation, SNe feedback

- effective "non-bursty" star formation history (inefficient baryon → DM energy injection)

- **global galaxy properties <u>very similar</u> (<10%) to CDM**

First hydrodynamical simulation of a galaxy in a SIDM cosmology

zoom-in simulations of an isolated halo (~10^{10} M_{sun})

same ICs: CDM and 4 SIDM cases (constant and velocity-dependent)

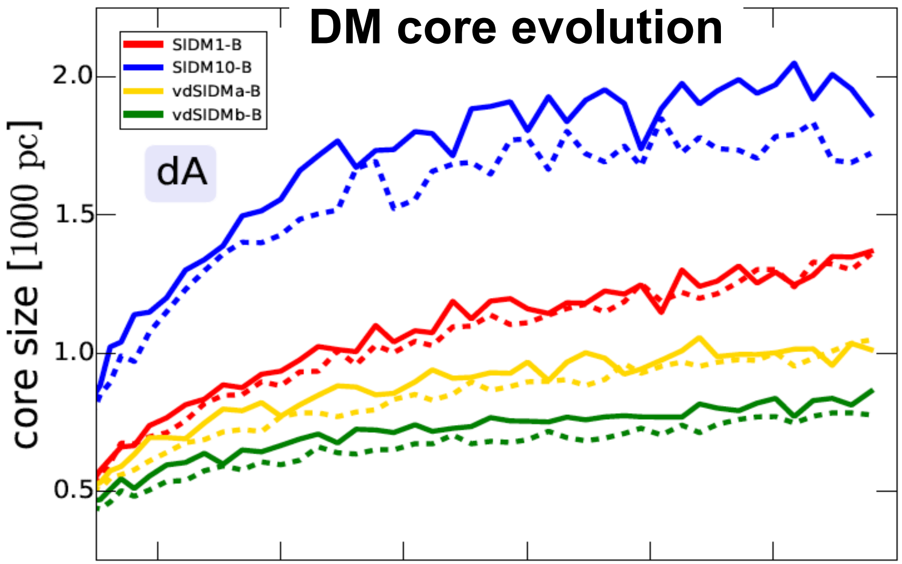
$m_{\rm dm}$ $[10^2\,{\rm M}_\odot]$	$m_{\rm baryon}$ $[10^2\,{\rm M}_\odot]$	ϵ [pc]	$N_{\rm DM}^{\rm hires}$
9.7	1.8	34.2	122,729,602
77.5	14.8	68.5	15,353,772

Results shown here for this resolution only

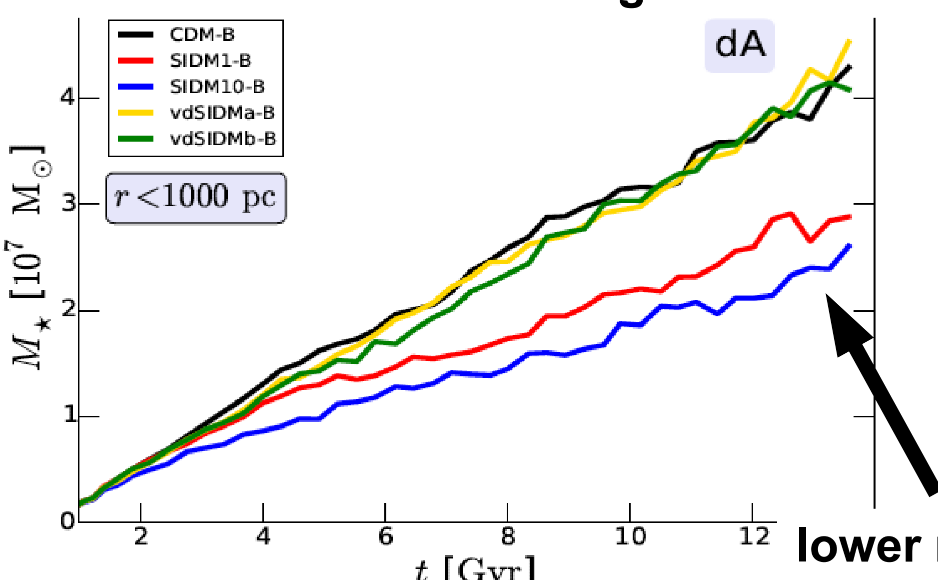
The stellar mass and metallicity are too high: our first goal is to compare both cosmologies under the same baryonic physics

Galaxies in a SIDM Universe

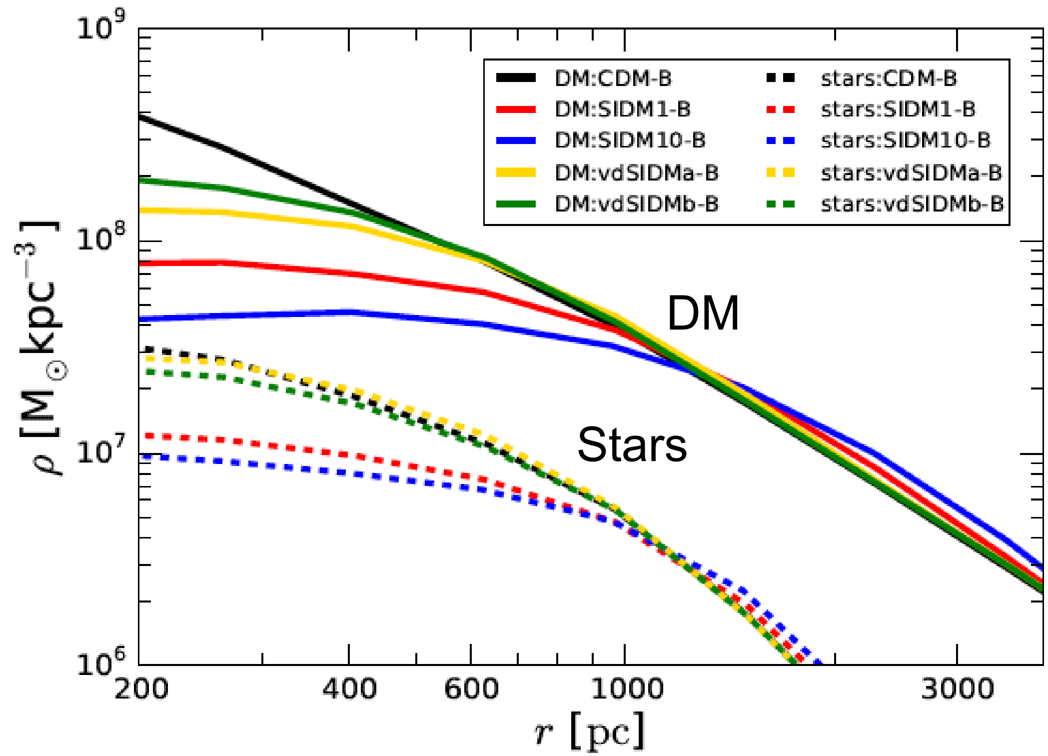
Vogelsbeger, Zavala+14



Central stellar mass growth



lower metallicity stars



Stellar cores tied to SIDM cores in DM-dominated systems (signature of DM collisions)

In baryon-dominated galaxies SIDM cores are tied to stellar distribution (Kaplinghat+14)

Concluding remarks

- **CDM/WDM/SIDM are by themselves incomplete DM theories**, they need completion with a particle physics model (all beyond SM: “exotic”)

- Decisive decade for “standard” DM model (CDM + WIMPs): experiments reaching the “expected” WIMP cross sections (Fermi, LUX,...)

- An effective (more generic) theory of structure formation **must consider a broader range of allowed DM phenomenology** (initial P(k), DM interactions,..) coupled with our developing knowledge of galaxy formation/evolution

Concluding remarks

SIDM is a competitive effective theory of structure formation:

- it preserves the large-scale successes of CDM and “naturally” avoids most of its small-scale (dwarf galaxies) challenges (**partially proof of concept only**)
- first hydro simulations in SIDM indicate that galaxy formation and evolution proceeds in a similar way as in CDM (nothing catastrophic!)
- the effect of DM collisions however, might be imprinted in the phase-space distribution of stars in dwarf galaxies at an observable level:
  dwarf galaxies might hide a clue of a fundamental guiding principle for a complete DM theory

Possible degeneracies in observational comparisons, albeit undesirable, reflect our current incomplete knowledge of the DM nature and galaxy formation/evolution